

The transistor at 50: not even considering retirement

BILL SCHWEBER, TECHNICAL EDITOR

Two mass-market products demonstrated what the transistor could enable, as the "solid state" came to dominate electronics.

The year 1947 finished with two far-reaching scientific breakthroughs. US Air Force Captain Chuck Yeager piloted the experimental X-1 rocket-propelled plane past the sound barrier on Oct 14. Many knowledgeable researchers thought such a feat would be impossible because the buildup of the shock wave around the plane would prevent it from penetrating the barrier. On Dec 16, a team at Bell Telephone Laboratories (the research arm of American Telephone & Telegraph, now part of Lucent Technologies) invented the transistor after years of deliberate research, experiments, trials, and false paths.

Breaking the sound barrier was a highly visible, well-publicized achievement, and it grabbed the public's imagination. The transistor's realization was a far quieter affair. The Bell Labs team demonstrated its invention to top management on Dec 23, but held off a public announcement until June 30, 1948, and published the results in the July 1948 issue of *Physical Review*. The general press gave the news scant coverage, but the technical trade press was somewhat more impressed: The now-defunct *Electronics* magazine used the transistor for its September 1948 cover story.

The first transistor circuit: Walter Brattain's lab notebook shows the circuit used to demonstrate the transistor as a microphone amplifier (courtesy AT&T Archives).

Dec 24 1947
3P129-7

We attained the following A.C. values at 1000 cycles
 $E_g = .016$ R.M.S. volts $E_p = 1.5$ R.M.S. volts
 $P_g = 5.4 \times 10^{-7}$ watts $P_p = 2.25 \times 10^{-5}$ watts
 Voltage gain 100 Power gain 40
 Current less $\frac{1}{2.5}$

This unit was then connected in the following circuit

This circuit was actually spoken over and by switching a distinct the device in and out a distinct gain in speech level could be heard and seen on the scope presentation with no noticeable change in ~~power~~ quality. By measurements at a fixed frequency

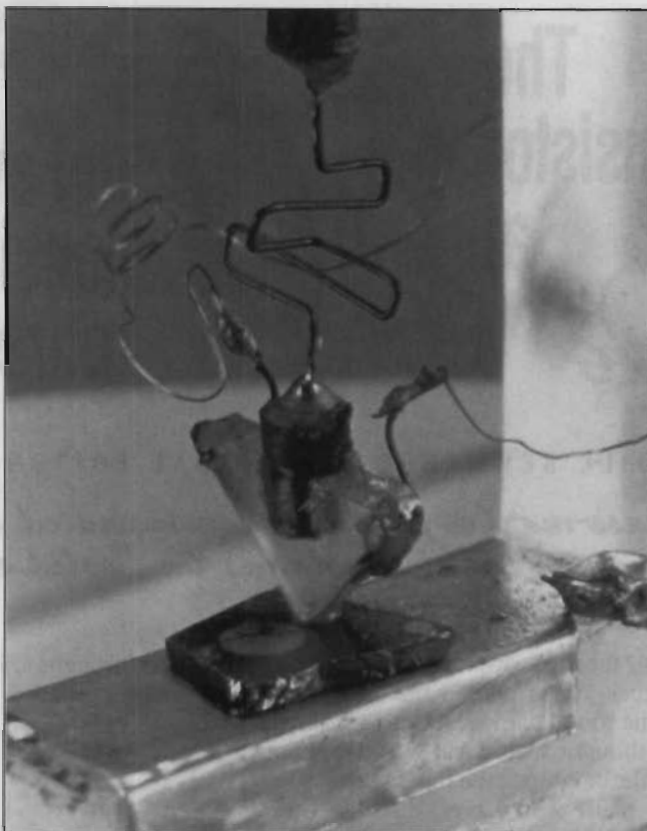
THE TRANSISTOR AT 50

As with many developments, few people foresaw the eventual impact of the transistor. Although its developers intended it to replace the vacuum tube in analog-telephony applications, the transistor led to much more than just instant-on radios and more reliable electronics. It completely changed electronic design, circuitry, components, manufacturing, and systems. It made analog easier; it made digital computers practical.

Technological developments in electronics during World War II made two things obvious to scientists, engineers, and industry leaders. First, electronic systems using vacuum tubes and relays could accomplish some fairly amazing things, such as radar, long-distance radio, basic TV, microwave repeaters, vacuum-tube booster amplifiers, and digital computers. Second, these systems would be constrained in their future potential because of the slow operation of relays, the heat dissipated by tubes, and the inherent relative unreliability of both.

Neither the tubes—invented by Lee De Forest—nor the relays were crude devices. They were fairly mature and sophisticated, as design and manufacturing engineers had pushed forward the state of the technology and production. Both, though, had reached a plateau, with diminishing likelihood for significant improvement. The limitations of tubes and relays would soon stifle major progress.

The Bell Telephone System was one of the largest users of tubes and relays and so had the greatest demand for something better than the tube. In addition, Bell Labs had expertise in the various research disciplines necessary to look in another direction for something to fill the basic need: an analog amplifier for audio signals that was smaller, lower power, and more reliable



No one could have imagined that ICs with more than 1 million active devices would evolve from this germanium point-contact transistor (courtesy AT&T Archives).

than the tube amplifier and that would also supplant relays in basic signal-switching applications.

In 1945 and 1946, Bell Labs assembled teams to explore alternatives based on the semiconductor technology that had been developed for microwave diodes and power rectifiers during World War II. Many of the leading solid-state physicists and materials scientists—led by John Bardeen, Walter Brattain, and William Shockley, who received the Nobel Prize for Physics in 1956 for their transistor invention—took part in the research. Most of the research took place in Murray Hill, NJ (Reference 1).

By our standards, the inventors' understanding of solid-state physics and the actions of electric currents and fields within semiconductors had many gaps and misconceptions. However, they knew that they were pushing theoretical knowledge along with their search for the solid-state amplifier.

They were quick to acknowledge when their observations and data didn't mesh with theory and revise their interpretations of the data, rationales, or hypotheses. Their proof of success was dramatic and simple: a one-transistor-microphone audio-amplifier circuit. Listeners could clearly hear the change in loudspeaker volume, as well as see it on the oscilloscope.

That first transistor was a germanium point-contact device. Although the Bell Labs team knew the potential semiconductor advantages of silicon, such as its higher bandgap energy, it was much harder to fabricate relatively pure crystals with silicon than with germanium. The point-contact structure itself was tricky to manufacture, with tiny wires contacting the material at precise locations, and had somewhat erratic characteristics. Still, manufacturers offered commercial point-contact devices for 10

years, beginning in 1951.

Late in 1948, Bell Labs developed the junction device, which it based on some additional theoretical work by Shockley. Junction transistors had better and more consistent performance than point-contact devices but consumed relatively large amounts of still-costly silicon; also, this configuration had its own problems with electrical contacts.

Through the 1950s, various improvements occurred in transistor design and fabrication. These improvements culminated in the 1960 development of the planar transistor, which built on, but differed widely from, the original 1948 device. In the planar device, the base and emitter regions are diffused through holes in silicon-dioxide masks, both collector and emitter junctions terminate at the surface, and the electrical contacts are aluminum. In a parallel development, Jack Kilby of Texas Instruments produced the first

THE TRANSISTOR AT 50

IC, a 1.2-MHz phase-shift oscillator with 0.2V p-p output, in June 1958—but that's another story.

Although the volume of devices that the Bell system needed was significant, the transistor still had no visible effect on the average consumer. However, two products—one all analog and one mostly digital—changed all that. They also accelerated the now-common cycle of a mass-market product driving production improvements and lower costs, which led to more applications and in turn to more mass markets.

The first product was a basic AM transistor radio. Patrick E Haggerty led a team at TI in conceiving this idea in mid-1954 (References 2 and 3). (Note that Bell generously offered the basic transistor technology to all takers, and TI had purchased a license from Bell for \$25,000 in 1951.) The developers of this 5×3×1.25-in. radio intended it to fit into a man's dress-shirt pocket, operate from a 22.5V battery, and sell for \$49.95. In comparison, a standard five-tube table-top radio sold for less than \$15.

One notable fact about this small radio was that Haggerty wanted it onto store shelves by Christmas—less than six months away. He met this goal, which although impressive even by our fast-moving standards, is still more impressive when you consider that transistors were finicky, had never been in a mass-market product, and cost \$20 to \$100 each. In addition, the complementary small components, such as condensers (capacitors), inductors, and resistors, that the pocket radio needed did not even exist, and virtually everything had to be designed from scratch.

Circuitry challenges existed as well. Transistors were power-gain devices, unlike vacuum tubes, and there was relatively little circuit-application experience in using them. Designers had to contend with devices whose performance was continually improving (generally a good characteristic, although

you risk oversize) but erratic with wide variations around typical specifications (which threatened unreliable circuit performance). Gain of these ger-



Three men and a transistor: Walter H Brattain (left), William Shockley (seated), and John Bardeen (right) invented the transistor at Bell Labs in December 1947. The trio received the Nobel Prize in Physics in 1956 for their discovery of the transistor effect (courtesy AT&T Archives).

manium devices was around 20 to 22 dB in the first stages at the 260-kHz IF band.

The first radio breadboard used six transistors. The TI group linked with a team led by Richard Koch from the Regency Division of IDEA (Industrial Development Engineering Associates), a manufacturer of TV boosters and other electronics, to make the breadboard into a manufacturable, low-cost product. The final circuit used four TI transistors, because the Regency team replaced one of the original six with a diode and combined the separate local-oscillator and mixer stages into one, thus eliminating another transistor.

The TR-1 radio was a tremendous success for Regency and TI, which sold more than 100,000 units during the first year. Equally important, it advanced the state of the art in transistor manufacturing, product design and development, and high-volume manufacturing. Companies used to testing systems by replacing tubes could no longer do so because transistors were usually soldered into the circuitry.

The radio also made IBM take notice. Thomas J Watson Jr of IBM used the radio to press his case to steer IBM away from using tubes in computers. TI got

several large transistor contracts from IBM, beginning in 1957. These occurrences culminated in a memo, which Watson co-authored, stating that IBM would build no more tube-based machines after June 1, 1958.

The impact of transistors was not just in analog circuitry, of course. Early computer circuits also used tubes and relays, but the enormous number of devices needed, with their heat and reliability issues, was a serious limitation to advancing computer technology. This limitation lies in sharp contrast to the tube AM radio, which was fairly reliable and needed only five tubes to provide reasonably good performance in its standard, mass-market version.

In the mid-1950s, the goal of transistor research was to improve the device's frequency performance and power handling so it could replace tubes in radio and communication applications. Unfortunately, higher power capability required larger transistors, whereas higher bandwidth needed smaller ones. Yet some in the industry realized that transistors could be more than solid-state analog amplifiers. The transistors' size and low power meant that designers could pack the devices closely in discrete circuits without excessive heating and also achieve low propagation delays within the devices.

This situation led to designers' use of transistors in basic digital gates. By 1964 and 1965, all-transistor desktop calculators from Friden, Sony, Wang Laboratories, and Hewlett-Packard were entering the market. These 30- to 40-lb units used CRTs or gas-discharge tubes for the user readout and quickly drove into oblivion the heavier, slower, noisier mechanical calculators that used thousands of gears and mechanical pieces. As the IC incorporated more

